"la Caixa" Foundation
Junior Leader
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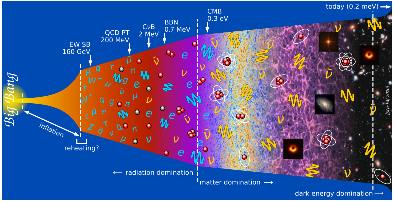
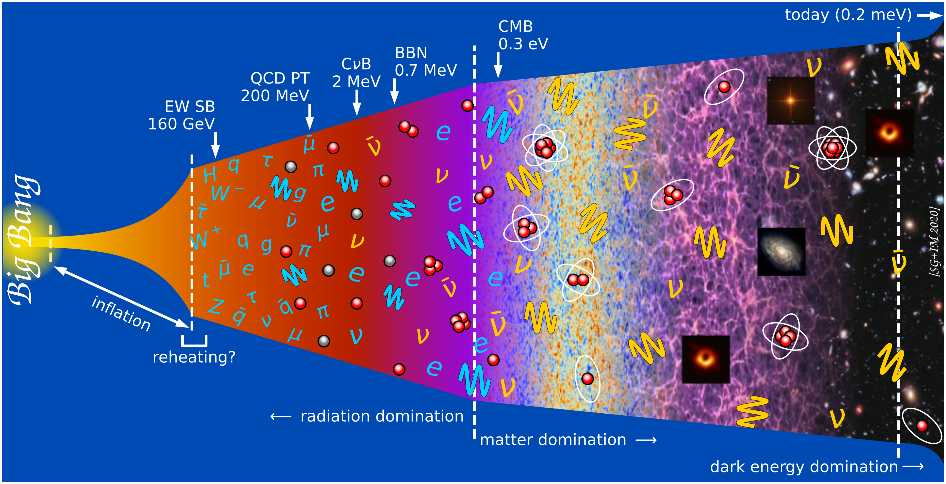
Neutrino decoupling in standard and non-standard scenarios

Based on JCAP 04 (2021) 073, JCAP 07 (2019) 014, JCAP 03 (2023) 046

TAsP meeting, Turin, 18-19/01/2024


today (0.2 meV)
CMB
0.3 eV
BBN
0.7 MeV
CνB
2 MeV
QCD PT
200 MeV
EW SB
160 GeV
Big Bang
inflation
reheating?
⟵ radiation domination
matter domination ⟶
dark energy domination ⟶
[SG+JM 2020]

History of the universe



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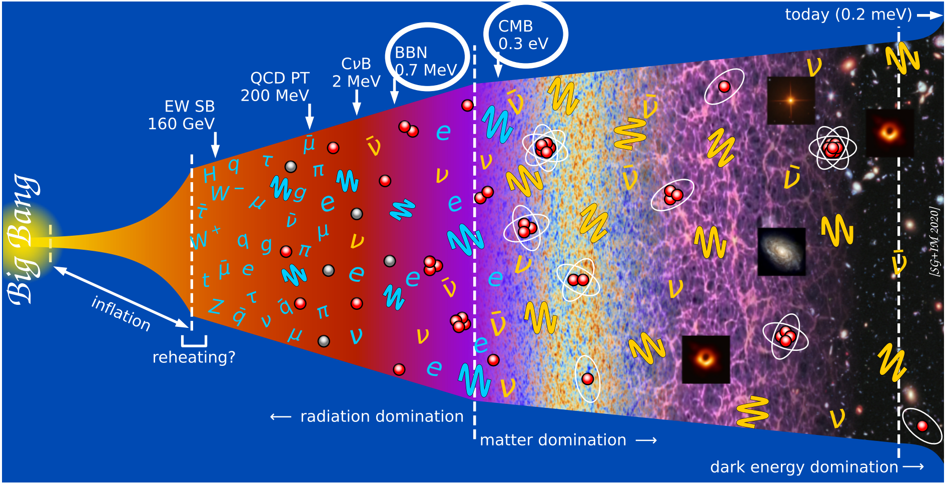

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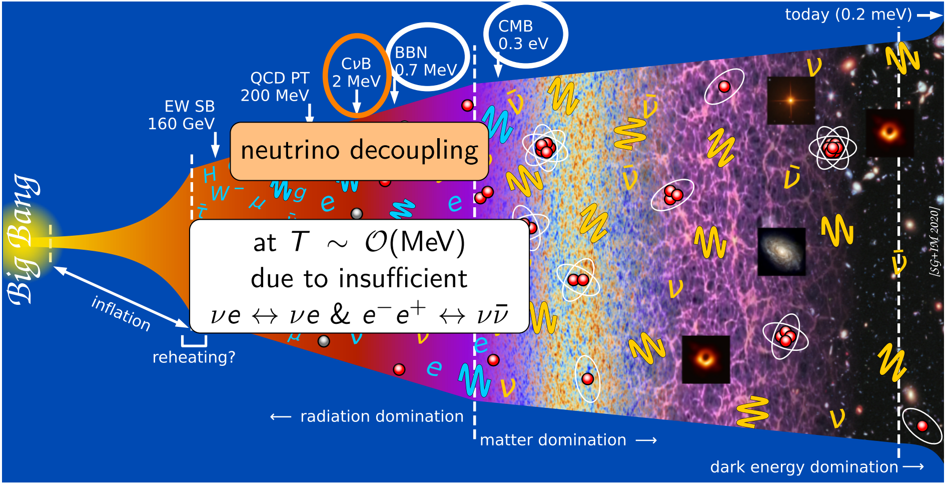


neutrino decoupling

at $T \sim \mathcal{O}(\mathrm{MeV})$
due to insufficient
$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

Relic neutrinos in cosmology: $N_{\rm eff}$

radiation density: $$\boxed{\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma}$$

ρ_γ photon energy density, $7/8$ for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

prediction:

instantaneous decoupling:
$N_{\rm eff} = 1$ for each ν family

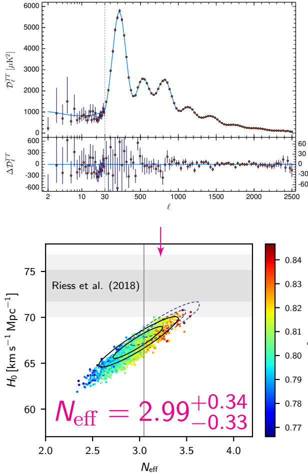
>3 because of entropy transfer
to photons when electrons
become non-relativistic

recommended value (3ν):

$$\boxed{N_{\rm eff} = 3.04}$$

[Bennett+, 2020] [Akita+, 2020]
[Froustey+, 2020] [Cielo+, 2023]

measurement:



$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$

[Planck 2018]

(95%, TT,TE,EE+lowE+lensing+BAO)

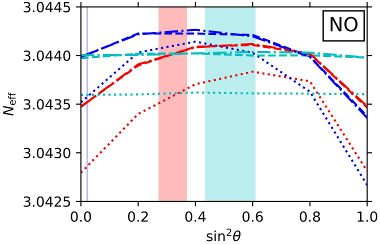
1 *Cosmic Neutrino Background*

2 ***Standard three neutrino scenario***

3 *Non-standard 1: light sterile neutrino*

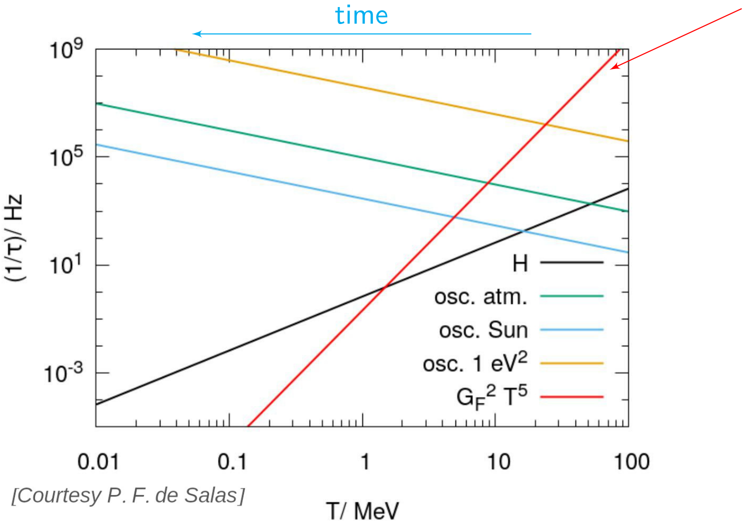
4 *Non-standard 2: non-unitarity*

5 *Conclusions*



Neutrinos in the early Universe

before BBN: neutrinos coupled to plasma ($\nu_\alpha\bar{\nu}_\alpha \leftrightarrow e^+e^-$, $\nu e \leftrightarrow \nu e$)



[Courtesy P. F. de Salas]

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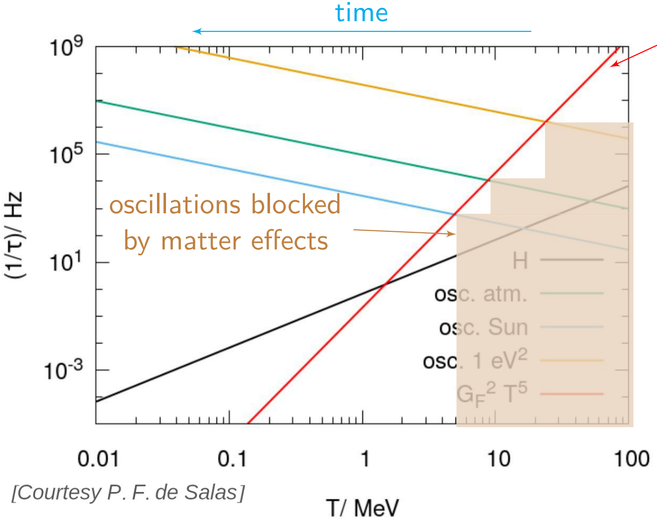

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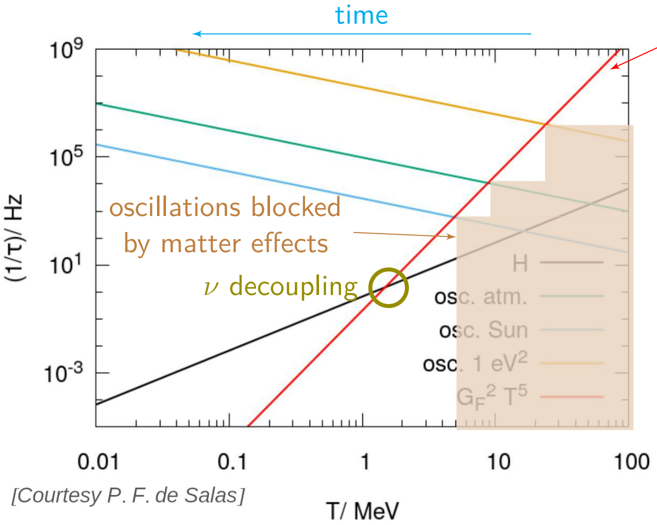

time

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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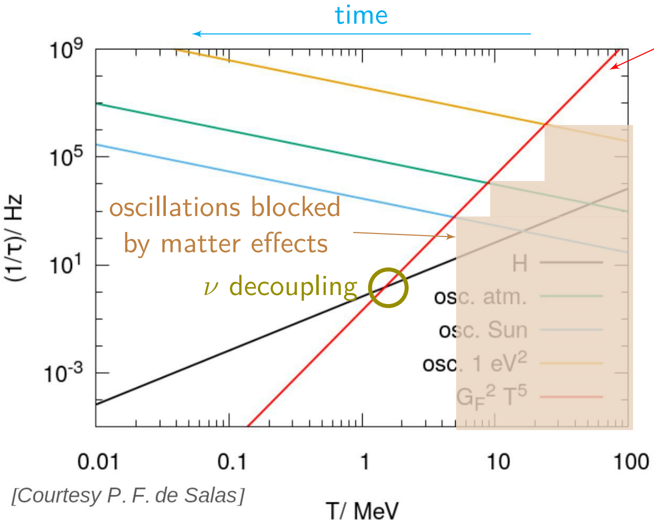

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[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3} T_\gamma$ after $e^+ e^- \to \gamma\gamma$

f_ν: frozen Fermi-Dirac distribution

Today:

$T_{\nu,0} = 1.945$ K $\simeq 1.676 \times 10^{-4}$ eV

$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}$ eV

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56$ cm^{-3} per family

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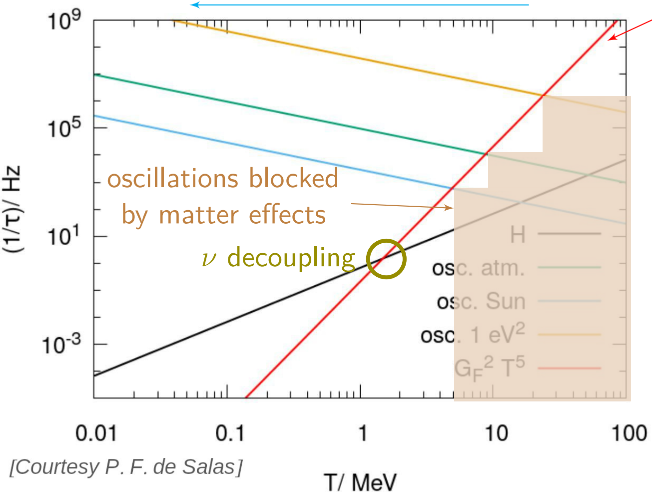

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]
[Sigl, Raffelt, 1993]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} \end{pmatrix}$

$\propto \langle a_j^\dagger(p,t)\, a_i(p,t)\rangle$

off-diagonals to take into account coherency in the neutrino system

ϱ evolution from $x H \dfrac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = -ia[\mathcal{H}_{\mathrm{eff}}, \varrho] + b\mathcal{I}$

H Hubble factor → expansion (depends on universe content)

effective Hamiltonian $\mathcal{H}_{\mathrm{eff}} = \dfrac{\mathbb{M}_{\mathrm{F}}}{2y} - \dfrac{2\sqrt{2}G_{\mathrm{F}}\, y\, m_e^6}{x^6}\left(\dfrac{\mathbb{E}_\ell + \mathbb{P}_\ell}{m_W^2} + \dfrac{4}{3}\,\dfrac{\mathbb{E}_\nu}{m_Z^2}\right)$

vacuum oscillations ← → matter effects

$\mathcal{I}$ collision integrals

take into account ν–e scattering and pair annihilation, ν–ν interactions

2D integrals over momentum, take most of the computation time

solve together with z evolution, from $x\frac{\mathrm{d}\rho(x)}{\mathrm{d}x} = \rho - 3P$

ρ, P total energy density and pressure, also take into account FTQED corrections

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`FORTran-Evolved PrimordIAl Neutrino Oscillations`
`(FortEPiaNO)`
`https://bitbucket.org/ahep_cosmo/fortepiano_public`

vacuum oscillations ←

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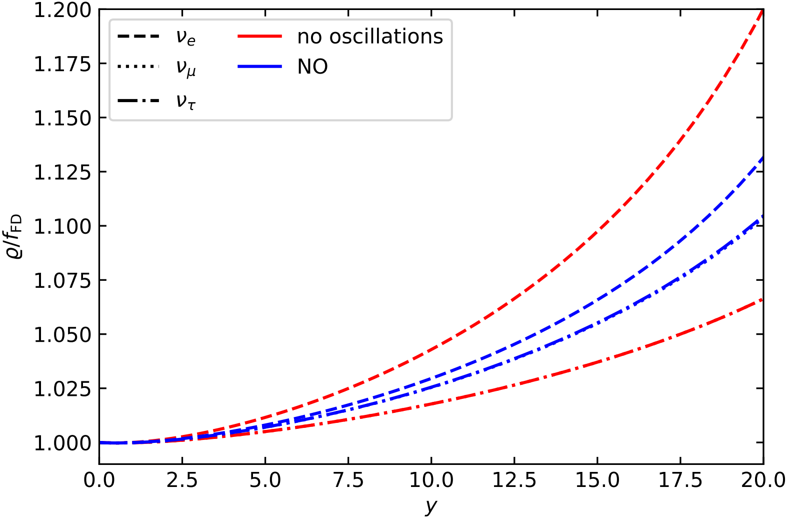
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

Distortion of the momentum distribution ($f_{\rm FD}$: Fermi-Dirac at equilibrium)

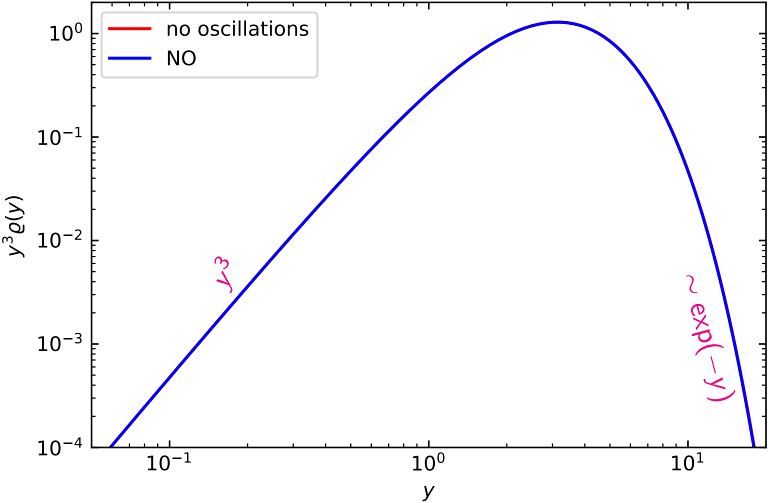


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

$$N_{\rm eff}^{\rm final} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{1}{\rho_\gamma}\sum_i g_i \int \frac{d^3p}{(2\pi)^3} E(p)\, f_{\nu,i}(p)$$

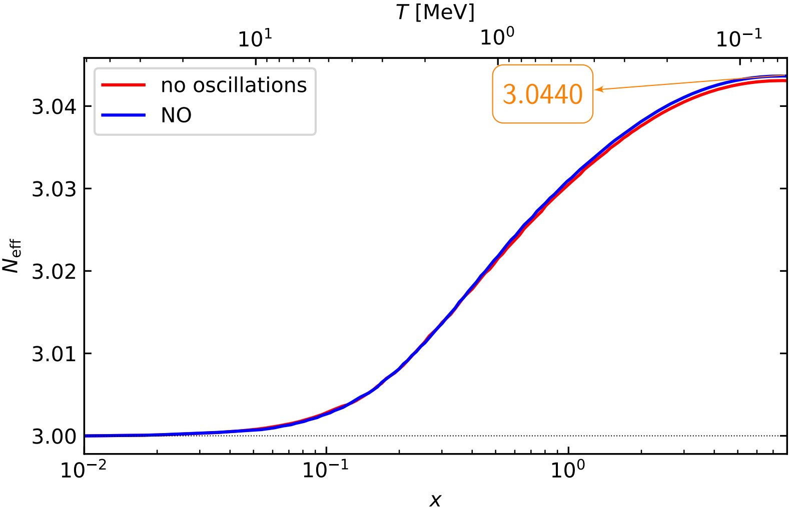
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



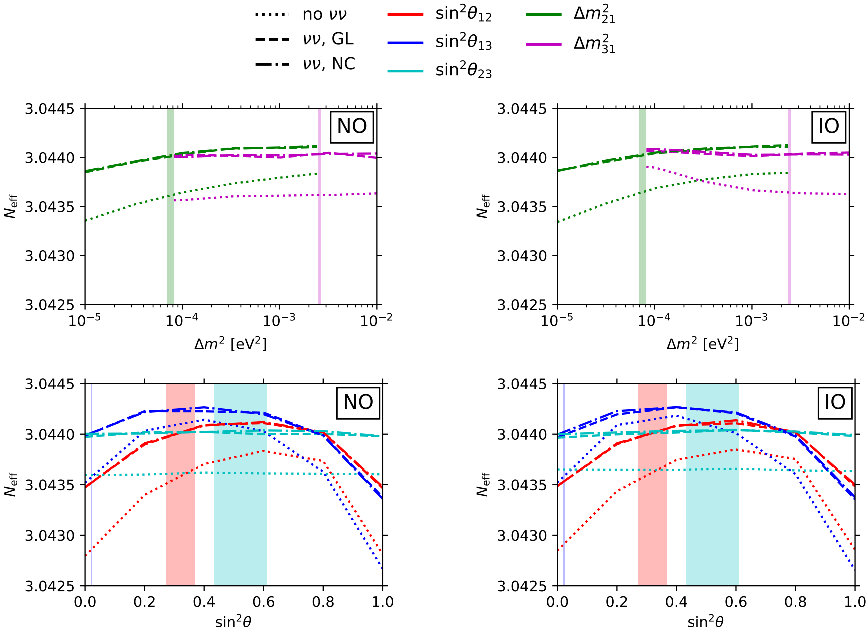
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

$$N_{\rm eff}^{\rm any\ time} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4\frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4\frac{1}{\rho_\gamma}\sum_i g_i\int\frac{d^3p}{(2\pi)^3}E(p)\,f_{\nu,i}(p)$$



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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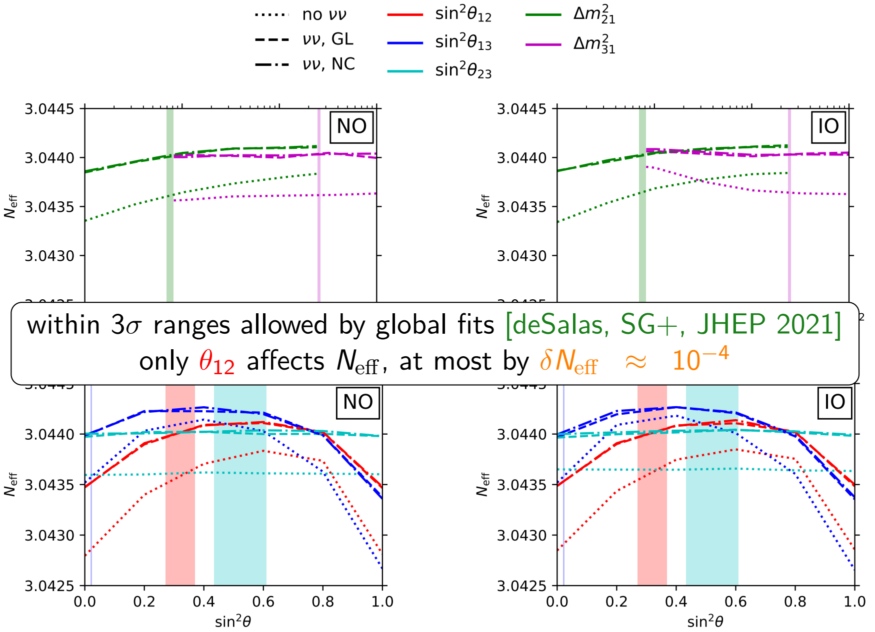
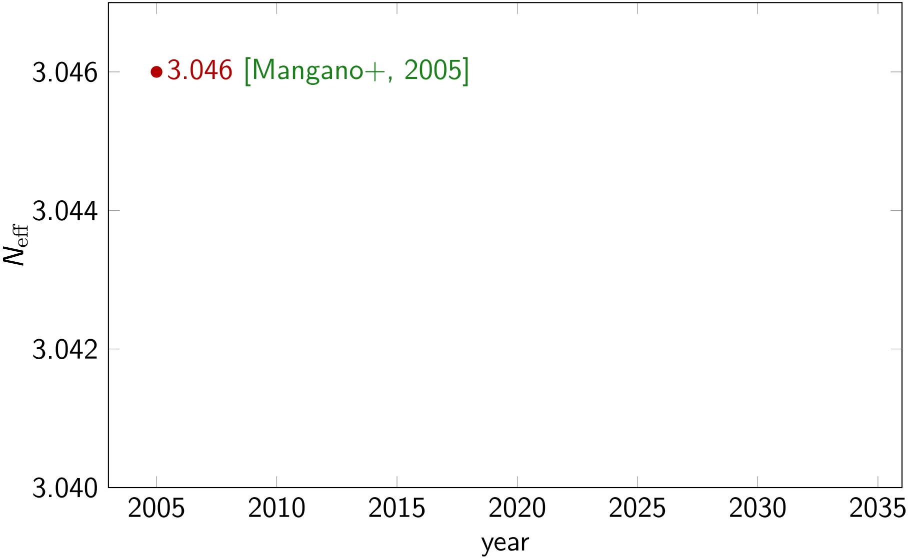


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]
only θ_{12} affects $N_{\rm eff}$, at most by $\delta N_{\rm eff} \approx 10^{-4}$

How precise is $N_{\text{eff}} = 3.04\ldots$?

Full 3ν mixing results:



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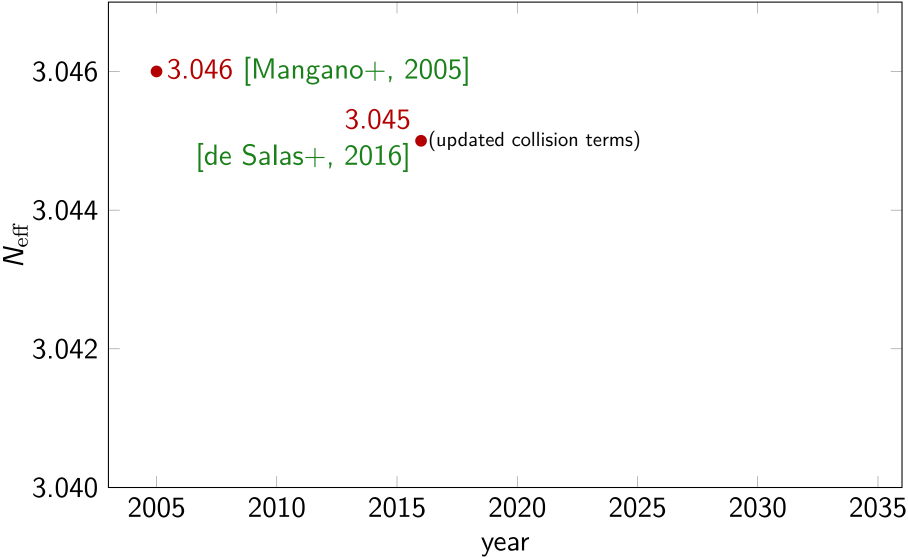

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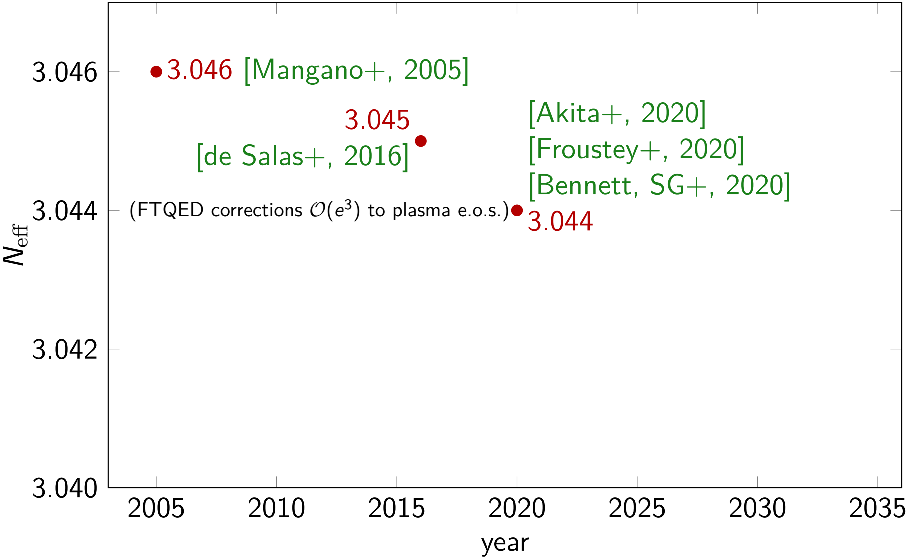

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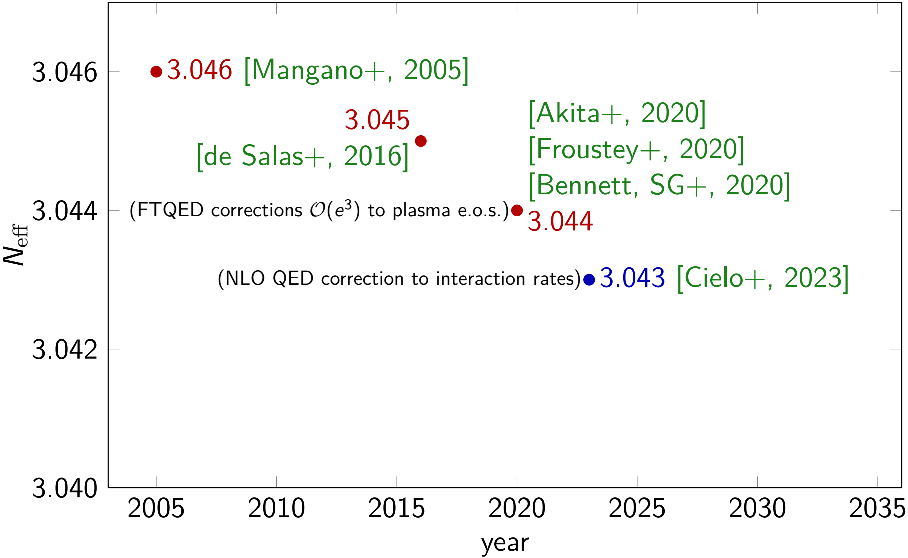

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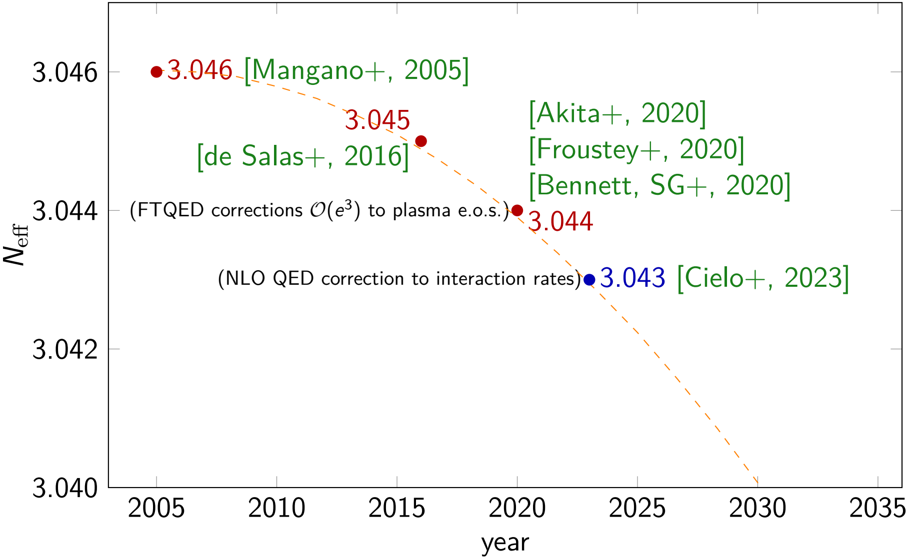

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2 Standard three neutrino scenario

3 Non-standard 1: light sterile neutrino

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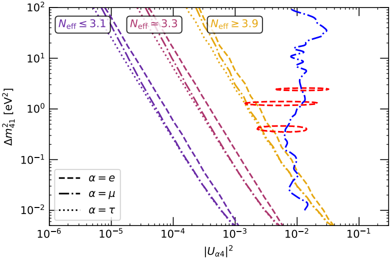
5 Conclusions



Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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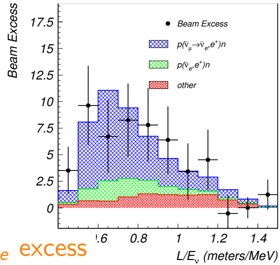
LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

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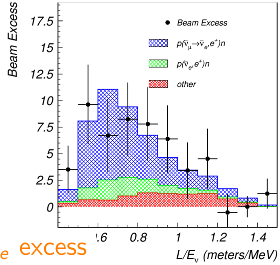

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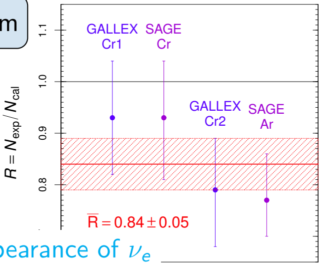
Gallium



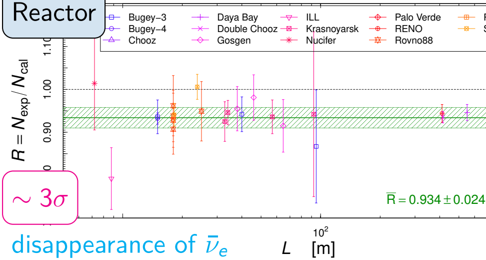
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

[Mention+, 2011] [Azabajian+, 2012]

Reactor



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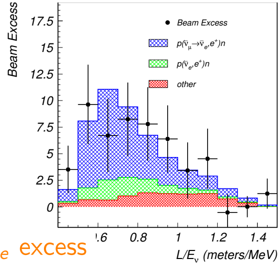

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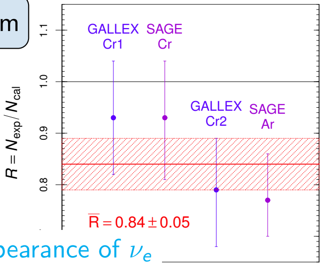

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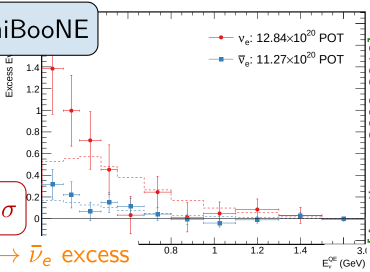
MiniBooNE



[Aguilar+, 2008-2018]

$\sim 5\sigma$

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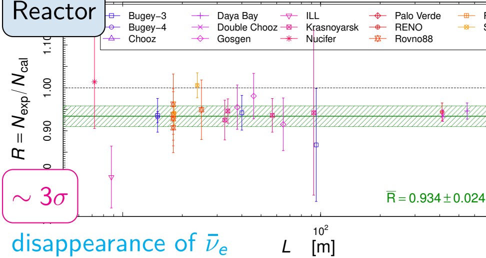

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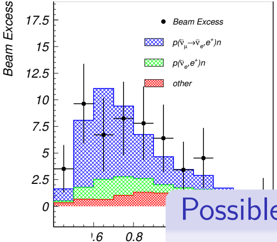

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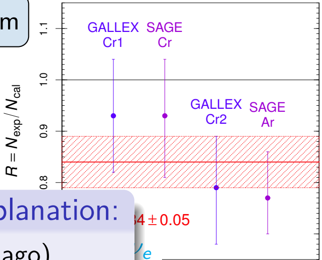


[Giunti, Laveder, 2011]

ν_e

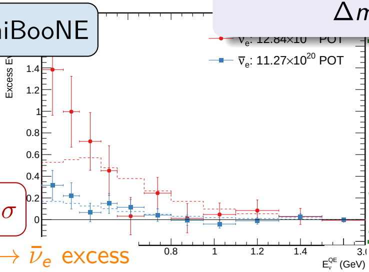
Possible common explanation:

(until a few years ago)

Additional squared mass difference

$\Delta m^2_{\rm SBL} \simeq 1 \text{ eV}^2$

MiniBooNE



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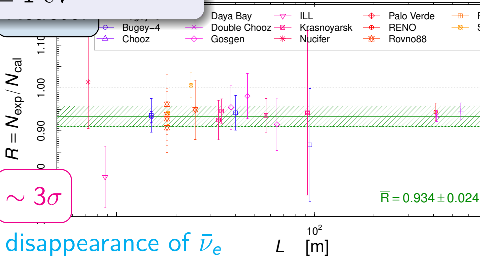

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L [m]

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[Bennett, SG+, JCAP 2021]
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density matrix: $\propto \langle a_j^\dagger(p,t)\, a_i(p,t) \rangle$

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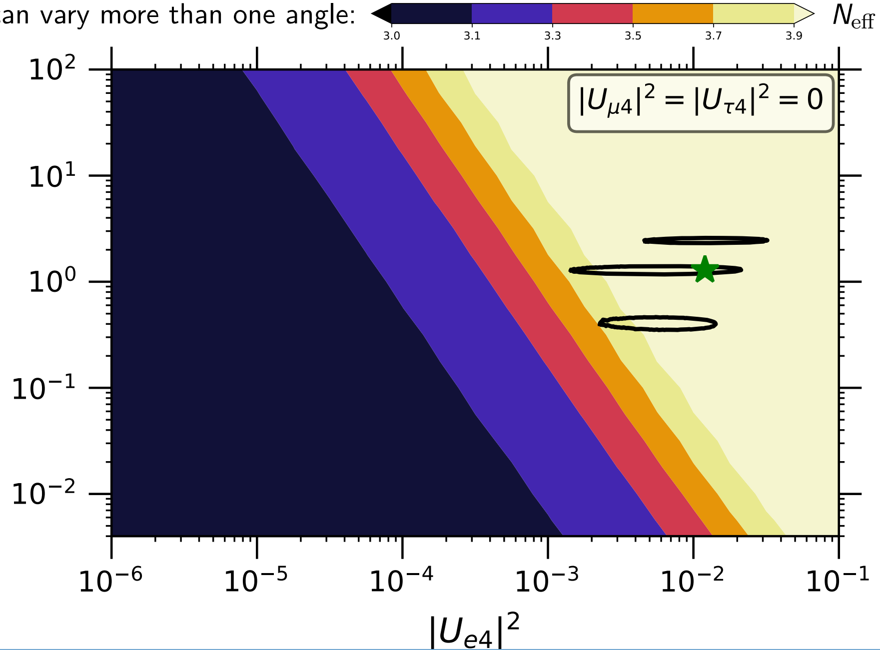
N_eff and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



$N_{\rm eff}$ and the new mixing parameters

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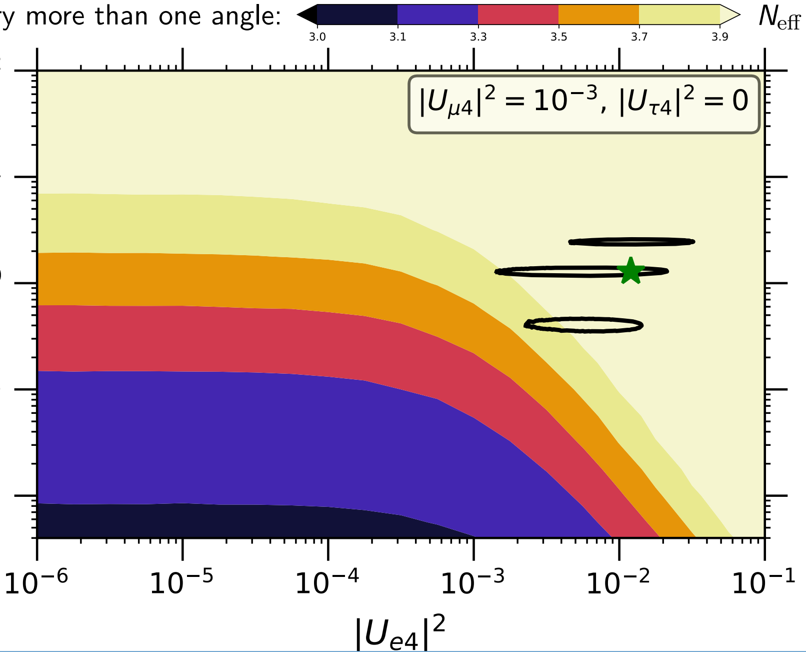

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[SG+, JCAP 07 (2019) 014]

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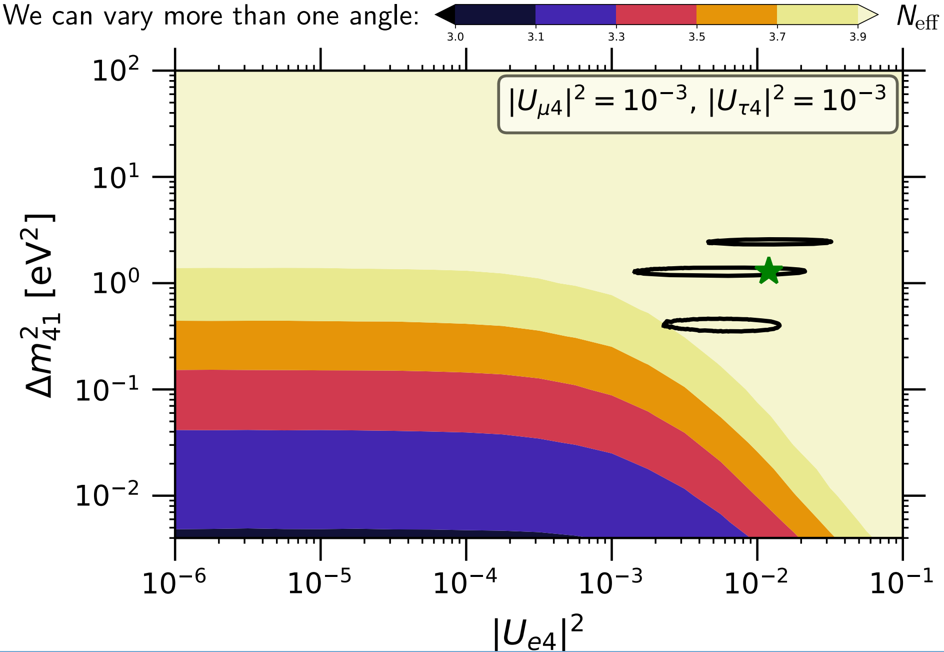
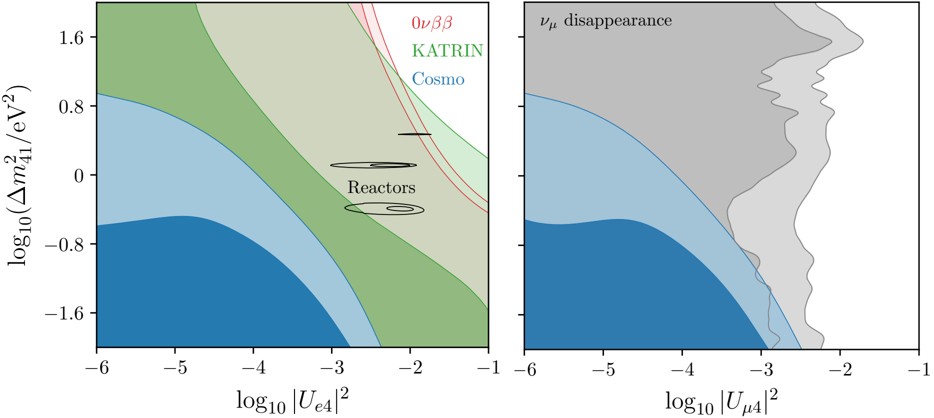


Comparing constraints

[PRD 104 (2021) 123524]

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!



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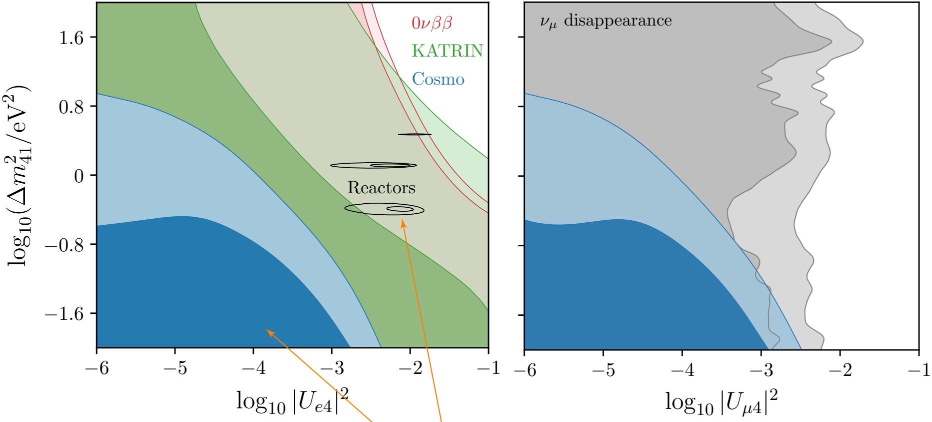

Warning: tension between reactor experiments and CMB bounds!

Comparing constraints

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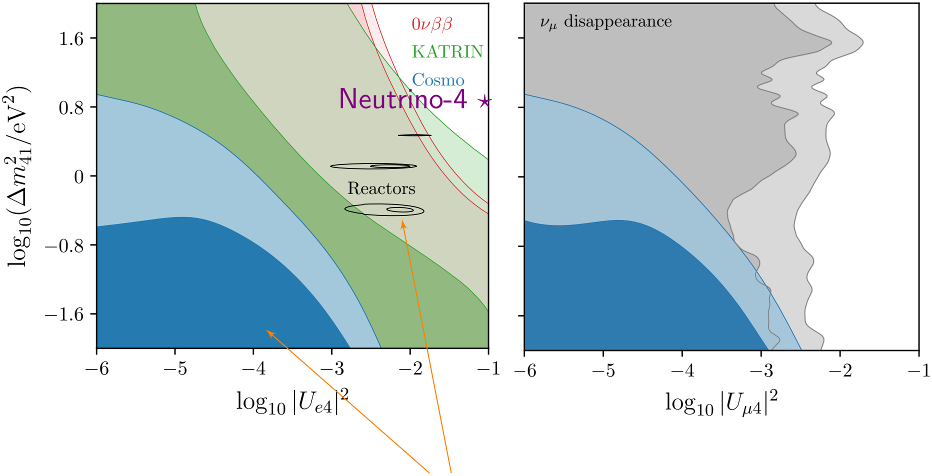

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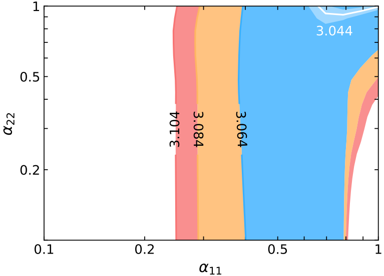

1
0.5
0.2
α_{22}
0.1
0.2
0.5
1
α_{11}
3.104
3.084
3.064
3.044

Non-unitarity of the 3 × 3 mixing matrix

[JCAP 03 (2023)]

Consider we have N_ν neutrino states

$$\text{Unitary } N_\nu \times N_\nu \text{ mixing matrix: } V = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & \cdots \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & \\ \vdots & & & \ddots \end{pmatrix}$$

the 3×3 sector (N)

describing mixing among lightest neutrinos

is non-unitary

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

α_{ii} real, α_{ij} $(i \neq j)$ complex ⇒ CP violation

$U = R^{23} R^{13} R^{12}$ is the standard unitary mixing matrix

Non-unitarity of the 3 × 3 mixing matrix

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Consider we have N_ν neutrino states

Unitary $N_\nu \times N_\nu$ mixing matrix: $V = \begin{pmatrix} \boxed{\begin{matrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} \end{matrix}} & \cdots \\ \vdots & \ddots \end{pmatrix}$

the 3×3 sector (N)
describing mixing among lightest neutrinos
is non-unitary

Neutrino interactions depend only on kinematically accessible states

Oscillations depend on all states

Oscillations with states $n > 3$ much heavier than $n \leq 3$
are averaged out at experiments

Non-unitarity and neutrino decoupling

[JCAP 03 (2023)]

Neutrino density matrix evolution in mass basis:

$$\left.\frac{\mathrm{d}\varrho(y)}{\mathrm{d}x}\right|_{\mathrm{M}} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho}}\left\{-i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{M}}}{2y} - \frac{2\sqrt{2}G_F y m_e^6}{x^6}\mathcal{E}_{\mathrm{M}},\varrho\right] + \frac{m_e^3}{x^4}\mathcal{I}(\varrho)\right\}$$

Unitary case

interactions:

$$\begin{aligned}(Y_L)_{ab} &\equiv \tilde{g}_L\mathbb{I} + (U^\dagger)_{ea}U_{eb}\\ (Y_R)_{ab} &\equiv g_R\mathbb{I}\end{aligned}$$

matter effects:

$$\mathcal{E}_{\mathrm{M}} = \frac{\rho_e+P_e}{m_W^2}U^\dagger\mathrm{diag}(1,0,0)U$$

Fermi constant:

$$G_F^\mu = G_F$$

Non-unitary case

interactions:

$$\begin{aligned}(Y_L)_{ab} &\equiv \tilde{g}_L(V^\dagger V)_{ab} + (V^\dagger)_{ea}V_{eb}\\ (Y_R)_{ab} &\equiv g_R(V^\dagger V)_{ab}\end{aligned}$$

matter effects:

$$\mathcal{E}_{\mathrm{NU}} \equiv \frac{\rho_e+P_e}{m_W^2}(Y_L - Y_R)$$

Fermi constant:

$$G_F^\mu = G_F\sqrt{\alpha_{11}^2\left(\alpha_{22}^2 + |\alpha_{21}|^2\right)}$$

$$G_F^\mu = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2}$$ [CODATA]

$$\mathcal{I}(\varrho) \propto G_F^2$$

Non-unitarity parameters and $N_{\rm eff}$

[JCAP 03 (2023)]

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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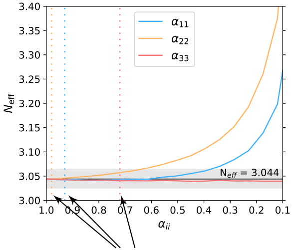
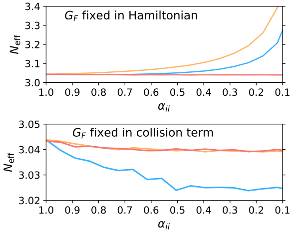


terrestrial bounds



Non-unitarity parameters and $N_{\rm eff}$

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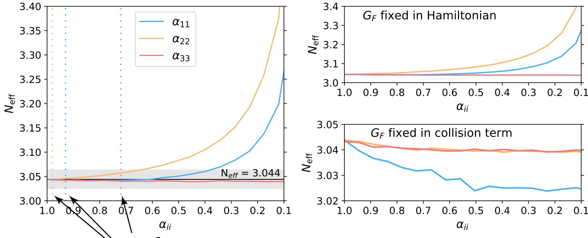
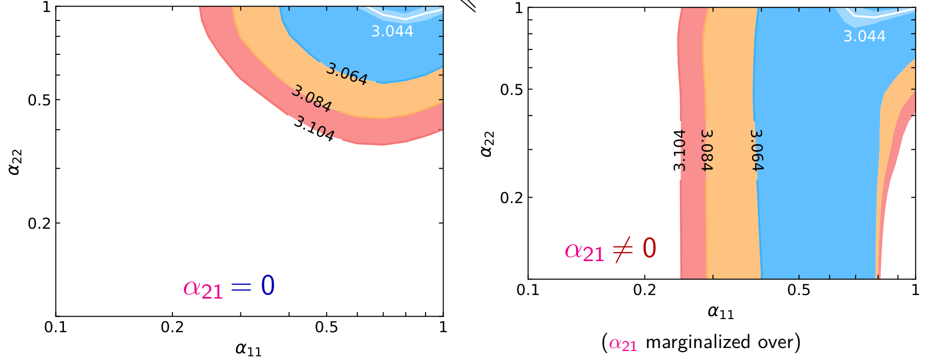




(α_{21} marginalized over)

Confidence regions from future CMB measurements with $\delta N_{\rm eff} = 0.02$

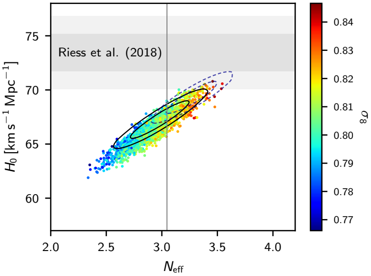
1 *Cosmic Neutrino Background*

2 *Standard three neutrino scenario*

3 *Non-standard 1: light sterile neutrino*

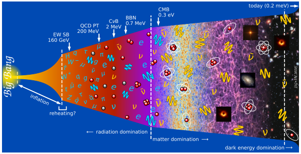
4 *Non-standard 2: non-unitarity*

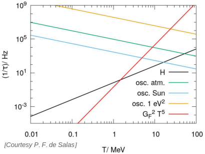
5 ***Conclusions***



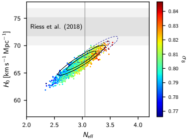
Conclusions

① Neutrinos in the early universe – probe lowest energies

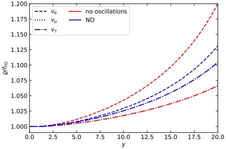


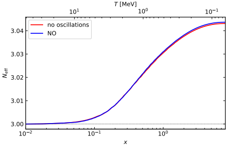


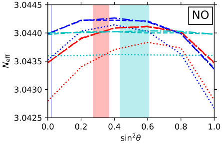
[Courtesy P. F. de Salas]



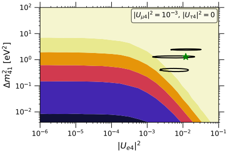
② Active neutrinos: precision calculations

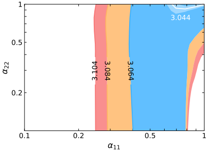






③ Non-standard scenarios: complementary bounds





Conclusions

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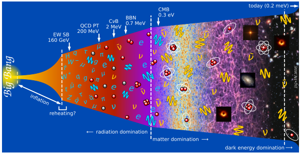

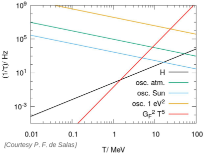

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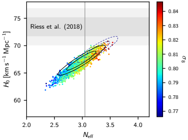
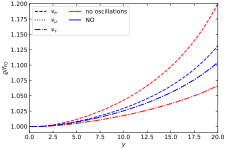
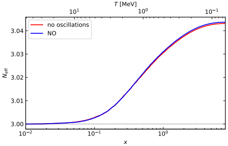
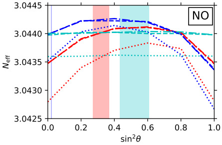


2 Active neutrinos: precision calculations







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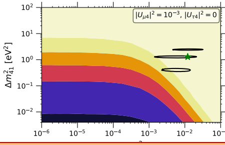

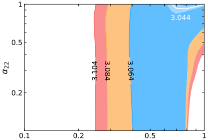

Thanks for your attention!